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Rotational and Magnetic Shunt Permanent Magnet Quadrupoles with Variable Magnetic Strength

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Abstract--   Next Linear Collider (NLC) and Very Large Hadron Collider (VLHC) projects suppose to use permanent magnets as bending, focusing and correcting elements. Prototypes of two permanent magnet quadrupoles with variable strength were built and successfully tested in Fermilab. Quadrupoles have 12.7 mm aperture diameter, 100 T/m gradient with an adjustment range of 0 to -20%. Special designs provide high precision magnetic center stability during strength change. SmCo5 permanent magnet bricks were used in these prototypes. Rotational quadrupole consists of four sections. Two central sections are rotated in counter directions to adjust the strength. Magnetic shunt quadrupole design provides variable shunting of the magnetic flux. The numerical simulation, designs, measuring results are described.

Index Terms—**Accelerator magnets, Permanent magnets, NLC, VLHC, adjustable, rotational quadrupoles, sliding shunt quadrupoles.**

I. INTRODUCTION

THE   Next Liner Collider (NLC) [1] and Very Large Hadron Collider (VLHC) [2] projects will require large quantity of various types accelerator magnets. The use of permanent magnets in various areas of the proposed accelerator projects has been evaluated and looks promising. Perhaps one of the significant steps that lead to the present emphasis on permanent magnets is the recent data from the Fermilab Recycler where extensive use of hybrid permanent magnets was implemented. By hybrid we mean that iron poles determine the magnetic field and the permanent magnet material acts to excite the magnetic field. Quadrupole, dipole and combined function magnets were fabricated, installed in the Fermilab Main Injector tunnel and commissioned with beam. It is the largest storage ring based on permanent magnets [3].

Permanent magnets have following advantages for future accelerators:

- very high energy in magnet aperture
- compact magnet system
- eliminate power supplies and long cables
- no water or LHe cooling and no vibration
- low cost.

Permanent magnets benefit from large progress in magnetic properties of rare-earth materials during the past decade. The maximum energy product increases from 200 kJ/m^3 to 400 kJ/m^3. The new technological processes and large scale applications like automotive industry drive permanent magnet materials to better performance and lower cost. The new Nd-Fe-B materials have best magnetic properties but lower radiation resistance and lower temperature   stability.

II. PERMANENT MAGNET PARAMETERS

The Next Linear Collider will have ~ 7000 magnets and at least 50% of them can be permanent magnets. Mostly it will be quadrupole magnets for beam focusing. The high magnetic field gradient in the range 100-200 T/m in the aperture 12.7 mm diameter will reduce the tunnel length and provide some cost savings. All quadrupoles should have possibility to adjust integrated field strength in the range 0 to -20% during 5 sec with 1-micrometer magnetic center stability. The Beam Based Alignment (BBA) system uses the quadrupole strength change to obtain the information about beam position relatively quadrupole magnetic center to match the magnet with the beam center. Align tolerance in the magnetic center stability is a very difficult task for permanent magnet design. Several prototypes have been investigated in Fermilab during the past two years.

III. SLIDING MAGNETIC SHUNT QUADRUPOLE

One of the options to change the magnetic field in permanent magnet system is to use ferromagnetic shunts, which short-circuit some part of magnetic flux generated by permanent magnets. A permanent magnet quadrupole with movable outer cylindrical magnetic shunt is shown on Fig. 1.
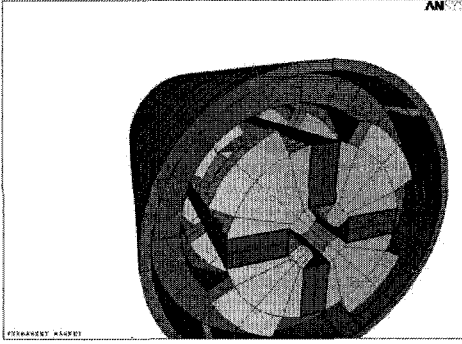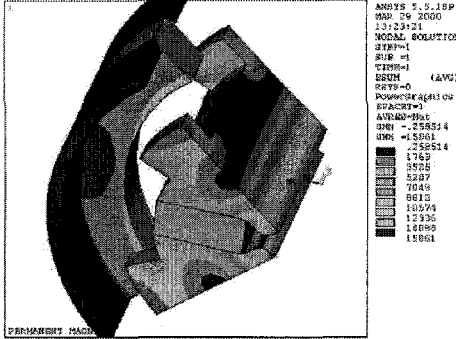
Fig.1. Sliding magnetic shunt quadrupole

For such complicated 3D geometry ANSYS code was used

to design the magnet. Magnetic field distribution for the case of maximum gradient is shown on Fig.2.

Fig.2 Magnetic flux density distribution for maximum field strength

The quadrupole strength can be adjusted by moving a sliding magnetic shunt in longitudinal direction. This quadrupole has maximum field gradient 100 T/m and gradient range of 16 %. The results of magnetic measurements (Fig.3) showed ~15 μm deviation from magnetic center when the strength was changed from 21.8 T to 25.8 T.
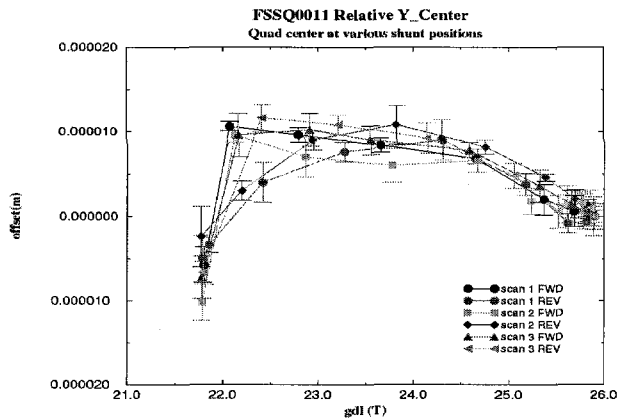

Fig.3. Magnetic center shift (mm) during integrated gradient change.

IV. ROTATIONAL PERMANENT MAGNET QUADRUPOLE

One of the main problems in adjustable quadrupoles is large magnetic forces, which resist any redistribution of magnetic energy and cause uncontrolled magnetic center shift. From this point of view the system with zero magnetic forces and magnetic energy redistribution is very attractive. It was proposed to investigate rotational permanent magnet quadrupoles (Fig.4). The close option was investigated [4], where Halbach's type permanent magnet quadrupoles were rotated to change the magnetic strength. Nevertheless, full magnetic forces were applied between the permanent magnet counter rotating parts. The FNAL rotational quadrupole consists of 4 identical permanent magnet quadrupoles fully magnetically screened from each other. Only two center sections are rotated in counter directions providing integrated field change. Fig. 4 shows this magnet assembly. All four sections are mounted on V-block and a simple mechanism provides ±30° rotation. Each section have four movable magnetic shunts (one per pole) to move the magnetic axis closer to the center of rotation as much as possible. The initial magnetic axis correction included sections rotation with their shunting in such a way to eliminate magnetic axis shift. The forces applied to rotated sections were low just to overcome a friction between V-block rails and outer magnet surface.
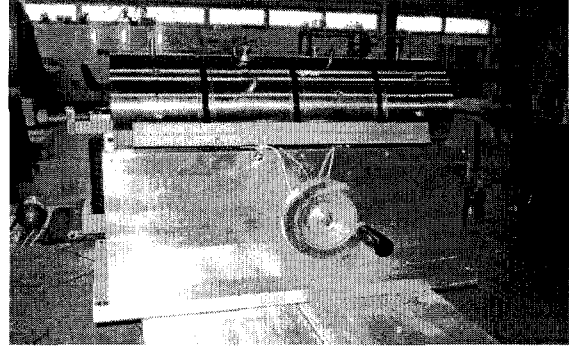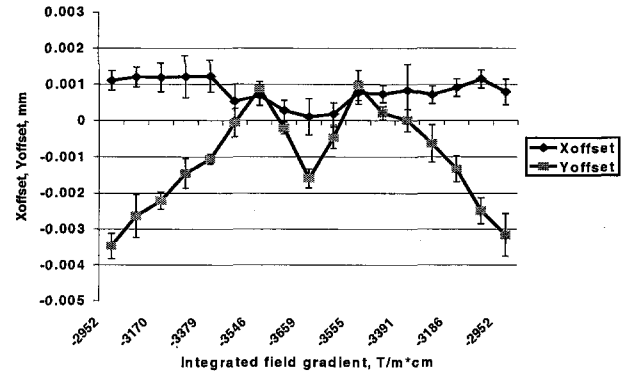

Fig. 4. Rotational permanent magnet quadrupole.

Fig.5. Magnetic center shift during positive and negative counter rotations.

This quadrupole was tested and the magnet axis stability of 4.5 μm was achieved for Y-axis and 1 μm for X (Fig. 5).

Some measurements showed better magnetic center stability and it is possible using better manufacturing technique to reach the goal of 1 µm magnetic axis stability with more accurately machined structure.

V. PASSIVE CORRECTION COILS

All previous results showed possibility achieve very high magnetic center stability for adjustable quadrupoles. Nevertheless for very long term applications such as future colliders it is rather risky explore the system without correction system. The magnetic center shift in quadrupoles is caused by a dipole magnetic field component. One micrometer magnetic center shift can be corrected by 1 Gauss dipole field generated by single turn coil with 1 A current. The shell type 20 turns correction coil was used to investigate this possibility. The magnetic center shift dependence from correction coil current is shown on Fig. 6. The magnetic
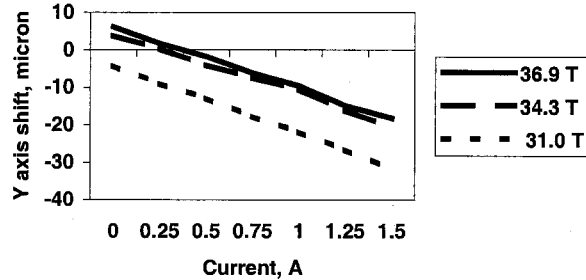

Fig.6. Magnetic center shift at different correction coil currents.

center shift is defined by correction current and an integrated gradient strength is

$$S = k \cdot Icor / (G \cdot Leff),$$

where Icor is correction coil current, G is quadrupole gradient, Leff is quadrupole field effective length.

The magnetic center shift correction was performed using these calibration curves. Fig. 7 shows the result of this calibration.
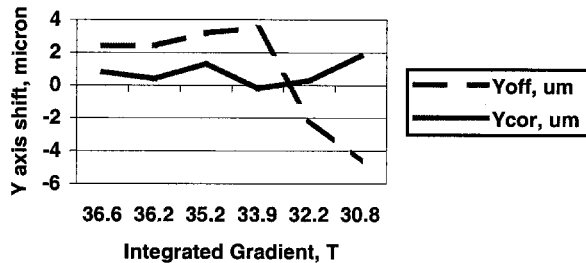

Fig.7 Results of correction magnetic center shift in Y direction.

Therefore, it is possible to correct the magnetic center shift using initially measured calibration curves. Fig. 8 shows

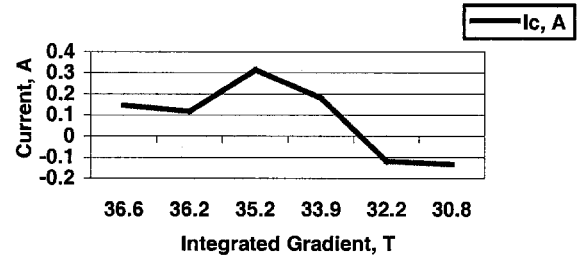correction coil current needed for the 1 µm accuracy correction.

Fig.8. Correction coil current at different fields.

VI. ACTIVE CORRECTION COILS

The passive correction coil system requires a strong demand to magnetic center shift reproducibility during all time of system operation. It is possible to eliminate this demand using active correction system. This system is based on measuring coils and correction coils. First coils measure the dipole field Bx,By changes during quadrupole strength change. An amplified signal is integrated and goes as a negative feedback signal to regulated power supply powering X and Y dipole correction coils. Such system will automatically eliminate dipole field components in magnet aperture and do not need strong calibration. Several watts power supply will be enough to compensate 20 µm magnetic center shift. Fig. 9 shows four cycles of 20% field strength adjusting and integrated signal induced in a measuring coil. The position of measuring coil is not critical, but the correction system will move the magnetic center to the coil magnetic center and the proper coil centering will reduce the needed correction power.
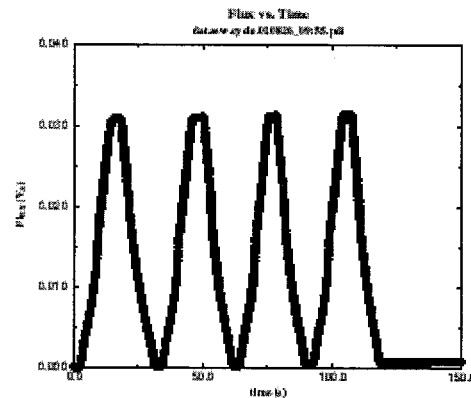

Fig.9. Integrated signal in measuring coil during 4 cycles strength change.

VII. EFFECTS OF BEAM ROTATION IN COUNTER-ROTATING QUADRUPOLES

In one of the proposed Beam Based Alignment procedures[1], all quadrupoles and BPM's are required to be consequently aligned during a 20% change in quad strength. If electron beam has offset in the aligning quadrupole, its position in the nearest upstream BPM, located in each quadrupole, will change with the changing strength. In rotational PM quadrupole the change of the strength is provided by counter-rotating two middle sections of four sections at the angle of ±30°. In case of rotated sectors the matrix of quad contains non-compensated skew components that provide vertical and horizontal coupling of the beam motion [5]. It can potentially complicate BBA algorithm. The effect of coupling motion was simulated for typical NLC lattice parameters. The result of simulation shows that difference in beam position in nearest BPM for traditional and Rotational PM quads is negligible. The traditional quad gradient is decreased to 0.8 of the nominal gradient when two middle sections of the permanent quad are counter-rotated by ≈26° to receive the same gradient.

Effect of coupled motion in rotational permanent quadrupoles was simulated also for the FODO lattice with the parameters close to the first sector of NLC beam line. In case when the beam energy increases from 10 to 20 GeV, the quad gradient increases along the beam line to keep constant beta function. For calculated beam line of 16 FODO cells the quad gradient doubled from first to last magnet. The results of simulation for "non-compensated" and "compensated" beam lines with PM quadrupoles are shown in Fig.10 and Fig.11 accordingly. In "non-compensated" beam line two middle sections in focusing and defocusing quads are rotated at same manner (+ϕ,-ϕ). In this case the coupling effect grow with the length, that leads increasing of effective vertical beam size (top graph in Fig.10) due to beam rotation (bottom) as compare with beam line of conventional quadrupoles.
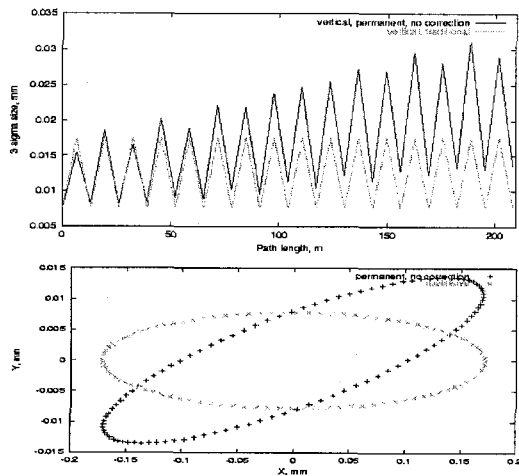

Fig.10. Vertical 3σ beam size (top) and x-y image (bottom) for "non-compensated" PM quads beam line. Result for conventional quads beam line is also shown for comparison.

In "compensated" beam line two middle sections in focusing and defocusing quads are rotated in opposite direction (+ϕ,-ϕ in D and -ϕ,+ϕ in F). It allows eliminate skew effect from rotational parts of quads (Fig.11). Non-compensated coupling results less than 15% deviation in vertical beam size with compare with uncoupled motion. Deviation in horizontal beam size in both cases is much smaller, because the horizontal beam emittance is two order of magnitude larger than the vertical one.
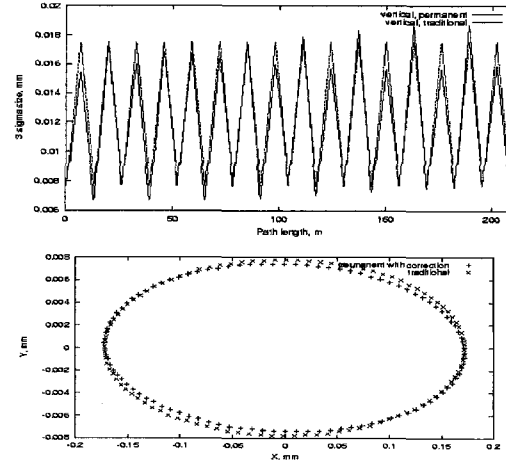

Fig.11. Vertical 3σ beam size (top) and x-y image (bottom) for "compensated" PM quads beam line. Result for conventional quads beam line is also shown for comparison.

VIII. CONCLUSION

Two adjustable permanent magnet quadrupole prototypes were investigated in Fermilab. The magnetic center stability of 1 μm was achieved for rotational quadrupole with passive correction coil. The option of active correction system will be investigated later. It was also shown that changing directions of rotation in focusing and defocusing quadrupoles could eliminate effect of beam coupled motion in rotating quadrupoles.

IX. REFERENCES

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